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Multiwavelength Rotation Curves to Test Dark Halo Central Shapes

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Abstract. We use Fabry-Perot Hα spectroscopy, complemented with published H I radio synthesis observations to derive high resolution rotation curves of spiral galaxies. We investigate precisely their inner mass distribution and compare it to CDM simulations predictions. Having verified the existence of the so-called core-cusp problem, we find that the dark halo density inner slope is related to the galaxy masses. Dwarf galaxies with $V_{max} < 100$ km/s have halo density inner slope $0 < \gamma < 0.7$ while galaxies with $V_{max} > 100$ km/s are best fitted by $\gamma \geq 1$.

1. Introduction

The dynamical masses of spiral galaxies are known to differ significantly from their visible masses. The commonly accepted cause is the existence of a ellipsoidal halo of unseen matter in addition to the stars and gas. The exact density distribution of these halos have become an increasingly important issue. On one side, N-body simulations of the cosmological evolution of the Cold Dark Matter (CDM) have now reached a sufficient resolution to predict the dark halo density profiles down to a scale corresponding to the inner parts of the spiral galaxies (Fukushige et al. 1997; Navarro et al. 1997; Moore et al. 1998; Ghigna et al. 2000). They almost always predict dense cuspy halos. On the other side, observations of dwarf spiral galaxies show shallow inner rotation curves, compatible with a flat density core (Blais-Ouellette et al. 2000, hereafter paper II).

The first step in showing the reality of this discrepancy is to eliminate the known possibilities of systematic observational biases. Two classes of errors could contribute to underestimate the velocities, hence the computed density, in the inner parts of spiral galaxies. The prime culprit in radio observations is the "beam smearing" effect due to the relatively low angular resolution of 21 cm data with sufficient sensitivity to detect H I in the outer part of spiral

galaxies. Combining the H I density gradient with the velocity gradient will lead to underestimate the velocity at a given radius.

Hα observations always easily reach an angular resolution where any beam smearing effect can be neglected. A less often commented source of uncertainties though is found in long slit observations, where most of Hα data come from. The lack of 2D coverage makes the alignment of the slit crucial to retrieve the real kinematics of a galaxy. Missing the kinematical center, which is not always the photometric center (paper II), or just a few degrees between the slit and the galaxy position angle will also lead to an underestimation of the velocities. Inclination estimation, which has to be photometrically determined, is another major source of uncertainties. In addition, the presence of a bar would hardly be noticed and its effect would most probably be confounded with the rotational kinematics.

In order to hedge ourselves against these biases, we use Fabry-Perot high resolution Hα spectroscopy combined with published radio synthesis observations to study the mass distribution of 8 dwarf and spiral galaxies. In paper II, with a smaller sample, we focused on modeling the mass distribution using different shape of dark matter halos. Here, in addition, we address the more precise question of what inner density slope (γ) halo can have for a given galaxy type or mass.

In section 2, we first briefly review the mass modeling used in the study. Then, in section 3, we look at detailed mass models of a few galaxies. In section 4, the relation between γ and galaxy mass is discussed followed by concluding remarks.

2. Modeling the Mass Distribution

To investigate in details the mass distribution of dark matter halos without a few assumptions on the matter content of spiral galaxies, one would have to adjust a good dozen of parameters. First, the luminous matter distribution depends on the disk and bulge mass-to-light ratios (and their radial gradient), and on the bulge-to-disk ratio. The H I contribution have to be corrected for helium fraction. The dark halos can be non-spherical, in addition to the five parameters usually used to describe the radial density distribution. This general distribution function can be expressed as (see Paper II for details):

$$\rho(r) = \frac{\rho_0}{(c + (r/r_0)^\gamma)\,(1 + (r/r_0)^\alpha)^{(\beta-\gamma)/\alpha}} \qquad (1)$$

where ρ_0 and r_0 are characteristic density and radius, where c, included for ease of comparison with other works, can force the presence of a flat density core, where α and γ are respectively the inverse outer and inner logarithmic slopes, and β the transition parameter.

One could add the distance that is used to calculate the light distribution, and a central mass which is suspected to exist in most spirals.

For some of these constraints, a fixed value is well accepted. The mild or absent color gradient in spiral galaxies lead to a radially constant mass-to-light ratio. The helium fraction can be approximate to its primordial abundance. Distances are hopefully well constrained by independent means.

Otherwise, essentially three data sets can be used to constraint these parameters: luminosity distributions (visible an H I) and velocity field or, assuming axisymmetry, light profiles and rotation curve. The visible light profile, is used to determine the bulge to disk ratio. The other parameters are all to the charge of the rotation curve. Most of the luminous contributions are heavily constrained by the most inner parts of the curve leading to a possible degeneracy between central mass, bulge, inner disk and halo contributions. That is why, many studies including this one, tend to focus on dwarf galaxies where bulges are negligible and large central masses excluded by the rotation curve. Only there, can one put strong limits on the inner slope of dark halo density distribution. For these galaxies, luminous matter is dependent only on the disk mass-to-light ratio, and dark matter from the central density, the core radius, and the three shape parameters. From the latter, only γ, the inner slope, has a significant impact on halo shape at the scale of dwarf galaxies, α and β being very poorly constrained.

In our procedure, the visible light profile (eventually decomposed in its bulge and disk components) is inverted in a mass profile scaled by the mass-to-light ratios. The H I contribution is estimated from its distribution and multiply by 1.33 to account for helium. The halo shape is, in general, fixed to a known profile. We choose four profiles, widely used in the literature, that span, with some redundancy, through most possibilities. The cuspy profile from Navarro et al. (1997) is a canonical example of CDM simulation prediction, the pseudo-isothermal sphere, the profile from Kravtsov et al. (1998), and Burkert's profile (Burkert et al. 1995) are all cusp-less profile with different shape parameters. Rotational velocities from all the contributions are then added in quadrature and compare to the rotation curve using a standard χ^2 minimization.

3. Mass Models

3.1. The Sample

Beside the dwarf galaxies NGC 3109 and IC 2574 from paper II, the whole sample includes 3 fairly bulge-less spirals (UGC 2259, NGC 2403, and NGC 6946), and 3 earlier type spirals (NGC 5055, NGC 2841, and NGC 5985) from paper III. Details are given in Table 1.

3.2. The Results

Complete modeling, using the four models, of the most relevant cases are presented here. NGC 3109 and IC 2574 (from paper II) are re-analyze to correct for a numerical problem which underestimated the central density. They are good examples of CDM incompatible dwarfs. Are also modeled, NGC 2403, as an example of bulge-less small spiral compatible with any model, and NGC 5055, as an earlier type spiral with a bulge. Analysis of the whole sample will be presented in a future paper (paper IV). Error bars are the quadratic sum of: half the velocity difference between receding and approaching sides, half the correction for asymmetric drift, error cause by uncertainty on inclination, and statistical error($\sigma/\sqrt{N}$).

It is rather clear that NFW profile is incompatible with the two dwarf galaxies. These results are in line with most similar studies using H I (e.g. Côté

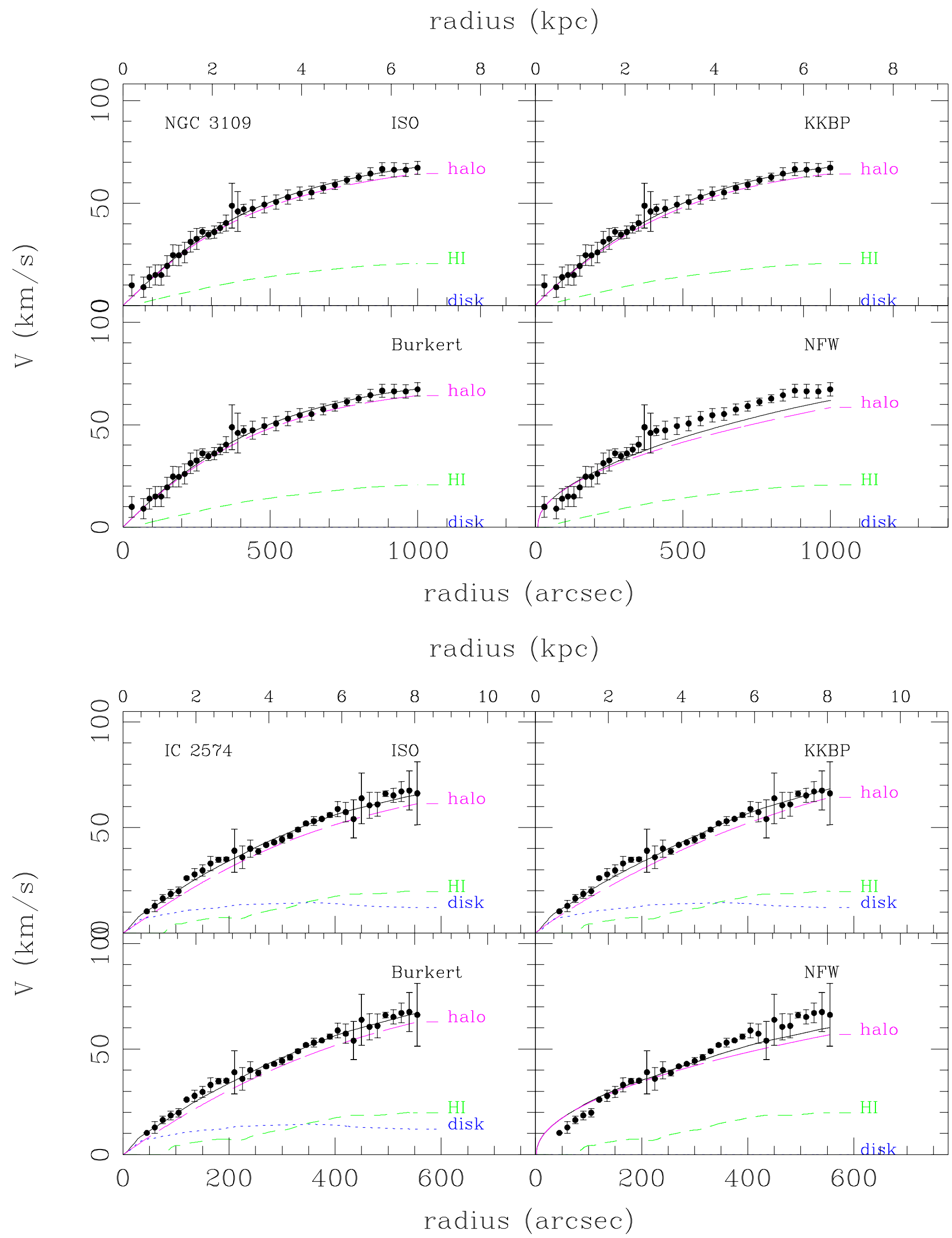

Figure 1. Best fit mass model for NGC 3109 (using the Hα up to 410″completed by the H I), and for IC 2574 (H I only).

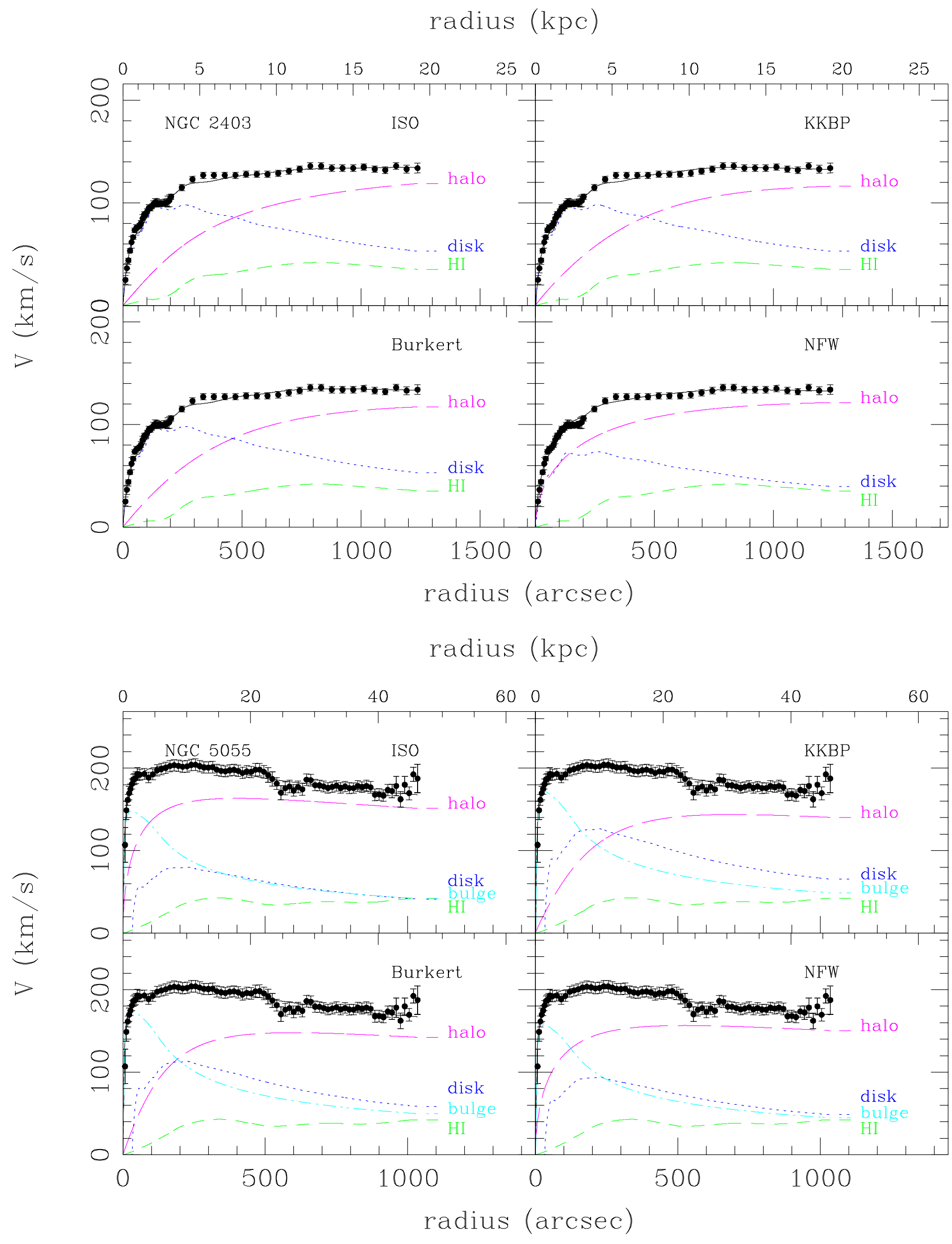

Figure 2. Same as Fig. 1 for NGC 2403 (using the Hα up to 345″), and for NGC 5055 (Hα is used up to 52 ″).

Table 1. Parameters of the sample. From the main references unless otherwise specified.

Name	Type	Distance	D_{25}	R_{HO}	α^{-1}	M_B	L_B	References		
		Mpc	$'$	$'$	$''$		$10^8 L_\odot$	H I	Hα	photom.
IC 2574	SABm	3.0	9.76	8.63	165	-16.87		m	cc	m
NGC 3109	SBm	1.36^n	14.4	13.3	234.9			o	cc	o
NGC 5585	SABd	6.2	5.27	3.62	46.7			p	gg	p
UGC 2259	SBcd	9.6^k	2.6	1.9	28.2	-16.33	5.06	b	ii	b
NGC 2403	SABcd	3.2^h	21.88	13.0	134	-19.50	7.9	c	ii	l
NGC 6946	SABcd	?	11.5	7.8	1.92	-21.38	530	d	ii	d
NGC 3198	SBc	9.15						c	nn	l
NGC 5055	SAbc	9.2^k	12.56	9.8	108.9	-21.15		e	ii	l

[a]This study
[m]Martimbeau et al. 1994
[n]Musella et al.97
[cc]paperII
[o]Jobin et al. 1990
[p]Côté et al. 1991
[gg]paperI
[b]Carignan et al. 1988
[ii]paperIII
[h]Freedman et al. 1990
[c]Begeman et al.1987
[l]Kent et al. 1987
[d]Carignan et al. 1990
[nn]Corradi et al. 1991
[e]Thornley et al. 1997
[i]Aaronson et al. 1983
[k]$H_0 = 75\,\mathrm{km\,s^{-1}}/\mathrm{Mpc}$

et al. 2000) or long slit observations (e.g. Swaters et al. 2000, de Blok et al. 2001) but without the related uncertainties (van den Bosch et al. 2000). It has to be noticed that higher resolution N-body simulations tend to give even steeper inner density slopes. The present discrepancy is therefore genuine and probably involve subtle phenomena or new physics.

Mass-to-light ratios tend to be unrealistically low for the smallest galaxies. Halo contributions are therefore an upper limit and are in fact probably shallower.

4. Halo Density Gradient

The range of possible observational biases that could explain the core-cusp problem is now significantly reduced, rather close to nil. The question of the physical cause of this shallow inner density distribution have been addressed many times leading to proposals ranging from multi-component dark matter (Burkert & Silk 1997) to self-interacting dark matter (Spergel & Steinhardt) and baryonic feedback processes. These scenarios are though to behave differently under different gravitational potentials. For example, feedback processes can hardly have an impact in galaxies with very deep potential. Plotting γ, the density profile inner slope, against the asymptotic rotational velocity would precisely show the evolution of this behavior. Figure 3 plots γ against the observe maximum velocity which, for NGC 3109 and IC 2574, is lower than the true asymptotic velocity.

The steepness of NGC 5055 rotation curve leads to an important degeneracy between γ, r_0 and rho_0. It is therefore not clear from the plot if there is a canonic value of γ around 1.2 that breaks down below 100 km/s or if γ is intrinsically increasing in massive galaxies.

Table 2. Parameters of the mass models

Model	Galaxy	Type	$(\mathcal{M}/L_B)_\star$ bulge	$(\mathcal{M}/L_B)_\star$ disk	r_0 kpc	ρ_0 $10^{-2}\mathcal{M}_\odot$ /pc^{-2}	χ^2
ISO	NGC 3109	SBm	no bulge	0.1	2.4	2.4	0.44
	IC 2574	SABm	no bulge	0.3	5.0	0.75	2.7
	NGC 2403	SABcd	no bulge	2.5	4.8	1.7	1.9
	NGC 5055	SABbc	2.3	0.8	8.2	3.4	0.55
Burkert	NGC 3109		no bulge	0.4	3.0	1.8	0.22
	IC 2574		no bulge	0.3	8.9	0.8	2.5
	NGC 2403		no bulge	2.5	8.0	1.9	1.8
	NGC 5055		3.2	1.6	8.2	2.8	.56
KKBP	NGC 3109		no bulge	0.0	4.0	1.7	0.5
	IC 2574		no bulge	0.3	10.5	0.46	2.5
	NGC 2403		no bulge	2.5	8.5	1.2	1.8
	NGC 5055		3.1	2.0	11.2	1.0	.56
NFW	NGC 3109		no bulge	0.0	605	0.0035	9.0
	IC 2574		no bulge	0.0	295	0.005	32
	NGC 2403		no bulge	1.4	11.8	0.9	1.4
	NGC 5055		2.6	1.1	10.8	1.8	.52

r_0: core radius of the dark halo
ρ_0: central density of the dark halo

5. Conclusion

We have modeled 8 dwarf and spiral galaxies using cusp-less and cuspy halos. The latter, predicted by CDM N-body simulations are clearly incompatible with dwarf galaxy kinematics. More precisely, galaxies with less than 100 km/s of maximum rotation velocity have a inner density logarithmic slope (γ) of less than .7 as opposed to $\gamma \geq 1$ predicted by the N-body simulations.

Presently, α, the outer density slope is poorly constrained by rotation curves. One need to reach a radius where the luminous disk contribution is negligible while the rotation curve is flat or decreasing (Carignan & Purton 1998). In our sample, UGC 2259 is a good candidate.

Future studies should in part extend to massive bulge-less galaxies to see if γ is intrinsically rising with galaxy mass or if it is constant, with a break down at low mass. The GHASP survey (Garrido & Amram 2002) should allow this kind of study.

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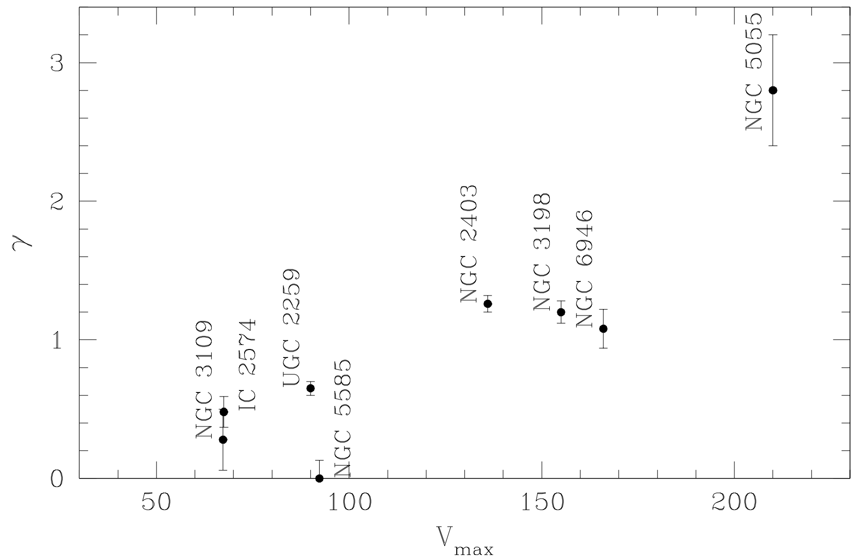

Figure 3. Inner logarithmic slope (γ) of the CDM halos. Note that N-body simulations give $\gamma \geq 1$.

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